

This project can be completed anytime after you have studied Section 11.8 in the textbook.



Many rockets, such as the *Pegasus XL* currently used to launch satellites and the *Saturn V* that first put men on the Moon, are designed to use three stages in their ascent into space. A large first stage initially propels the rocket until its fuel is consumed, at which point the stage is jettisoned to reduce the mass of the rocket. The smaller second and third stages function similarly in order to place the rocket's payload into orbit about the Earth. (With this design, at least two stages are required in order to reach the necessary velocities, and using three stages has proven to be a good compromise between cost and performance.) Our goal here is to determine the individual masses of the three stages to be designed in such a way as to minimize the total mass of the rocket while enabling it to reach a desired velocity.

For a single-stage rocket consuming fuel at a constant rate, the change in velocity resulting from the acceleration of the rocket vehicle has been modeled by

$$\Delta V = -c \ln \left(1 - \frac{(1-S)M_e}{P + M_e} \right)$$

where M_e is the mass of the rocket engine including initial fuel, P is the mass of the payload, S is a *structural factor* determined by the design of the rocket (specifically, it is the ratio of the mass of the rocket vehicle without fuel to the total mass of the rocket with payload), and c is the (constant) speed of exhaust relative to the rocket.

Now consider a rocket with three stages and a payload of mass A . Assume that outside forces are negligible and that c and S remain constant for each stage. If M_i is the mass of the i th stage, we can initially consider the rocket engine to have mass M_1 and its payload to have mass $M_2 + M_3 + A$; the second and third stages can be handled similarly.

1. Show that the velocity attained after all three stages have been jettisoned is given by

$$v_f = c \left[\ln \left(\frac{M_1 + M_2 + M_3 + A}{SM_1 + M_2 + M_3 + A} \right) + \ln \left(\frac{M_2 + M_3 + A}{SM_2 + M_3 + A} \right) + \ln \left(\frac{M_3 + A}{SM_3 + A} \right) \right]$$

2. We wish to minimize the total mass $M = M_1 + M_2 + M_3$ of the rocket engine subject to the constraint that the desired velocity v_f from Problem 1 is attained. The method of Lagrange multipliers is appropriate here, but difficult to implement using the current expressions. To simplify, we define variables N_i so that the constraint equation may be expressed as $v_f = c(\ln N_1 + \ln N_2 + \ln N_3)$. Since M is now difficult to express in terms of the N_i 's, we wish to use a simpler function that will be minimized at the same place as M . Show that

$$\begin{aligned} \frac{M_1 + M_2 + M_3 + A}{M_2 + M_3 + A} &= \frac{(1-S)N_1}{1-SN_1} \\ \frac{M_2 + M_3 + A}{M_3 + A} &= \frac{(1-S)N_2}{1-SN_2} \\ \frac{M_3 + A}{A} &= \frac{(1-S)N_3}{1-SN_3} \end{aligned}$$

and conclude that

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Tao Wei



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